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Mapping Ground-Level Radiation Fields with DREO's Airborne Gamma-Ray Spectrometer

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Abstract

An algorithm is developed and tested that infers a ground contamination pattern from the dose rate patterns measured by DREO's Airborne Gamma-ray Spectrometer. This algorithm is based on a least-squares minimisation, and uses Microshield calculations of dose rates as a function of altitude over a patch of contaminated ground. The algorithm is successful in that it correctly identifies regions of high and low contamination, which would permit a commander to identify areas to avoid, or paths to follow through a non-uniformly contaminated region. However, the contamination pattern predicted by this algorithm is not a high-fidelity facsimile of the actual distribution. The reason for this deficiency is likely that the problem of calculating ground-level contamination patterns from airborne measurements is inherently underdetermined, and evidence is presented to this effect. These results demonstrate clearly the utility of airborne survey for military purposes, and a method of analysing the data from such a platform.

Résumé

Un algorithme est développé et essayé qui implique une configuration de contamination au sol basé sur les débits de dose mesurées par le spectromètre aérien de rayonnement gamma de CRDO. Cet algorithme utilise la méthode de minimisation des moindres carrés, et aussi, des calculs de débits de dose effectués par Microshield en fonction de l'altitude au-dessus d'une section de terrain contaminée. L'algorithme fonctionne en ce qui concerne l'identification de régions de contamination élevée et basse. Ceci permettrait à un commandant d'identifier les zones à éviter, ou les voies d'accès à suivre lorsqu'il fait face a une région qui possède une configuration de contamination non-uniforme. Cependant, la configuration de contamination prévue par cet algorithme ne représente pas un modèle idéal de la distribution actuelle. La raison pour laquelle il existe ce problème est surement due au fait que le calcul des configurations de contamination au sol basé sur les mesures aériennes demeure un calcul qui n'est pas très bien défini. Il y aura preuve de ce phénomène présentée si peu. Ces résultats démontrent clairement l'efficacité de l'enquête aérienne dans un scenario militaire. galement, ils représentent une méthode d'analyser les données générées par de telles enquêtes.

Executive summary

Introduction: While it is clear that airborne radiation survey offers many advantages to the military, one of the biggest challenges remaining is the interpretation of data from an airborne platform. In trials conducted in September 1999 under the Franco-Canadian accord, DREO's Airborne Gamma-ray Spectrometer was flown over a non-uniformly contaminated field in Bourges, France. The analysis of these data is the subject of this report.

Results: An algorithm was developed that allows airborne measurements to be turned into ground-level contamination patterns. While this algorithm does not perfectly determine the ground-level contamination distribution, it certainly performs well enough to identify regions of high and low contamination. This is most important to military commanders who are planning operations in the contaminated area, or are trying to avoid the contaminated area entirely.

Significance: Recently, Canadian and other NATO defence departments have turned their attention to airborne radiological survey as a solution to some of the problems surrounding operations in a contaminated area. This work shows clearly the promise and limitations of this approach for military operations. It also presents a method with which data from such a sensor could be analysed so as to produce a worthwhile military product.

Haslip D. S., Cousins T., Jones T. A., Bouteilloux Ph., Dhermain J., Clifford E. T. H. 2000. Mapping Ground-Level Radiation Fields with DREO's Airborne Gamma-Ray Spectrometer. DREO TM 2000-121 Defence Research Establishment Ottawa.

Sommaire

Introduction: Malgré qu'il est clair que l'enquête aérienne de rayonnement offre plusieurs avantages au militaire, un des plus grands défis demeure l'analyse des données d'une telle plateforme. Durant les essais effectués en septembre 1999 sous l'entente Franco-Canadienne, le spectromètre aérien de rayonnement gamma de CRDO a été utilisé au-dessus d'une zone qui possède une configuration de contamination non-uniforme à Bourges, France. L'analyse de ces données est le sujet de ce rapport.

Résultats: On a développé un algorithme qui permet de traduire les mesures aériennes en configurations de contamination au niveau du sol. Tandis que cet algorithme ne détermine pas parfaitement la distribution de contamination au niveau du sol, il fonctionne certainement assez bien qu'il puisse faire la distinction entre les régions de contamination élevée et basse. Ceci représente un atout important pour les commandants militaires qui doivent planifier des maneuvres dans une zone contaminée, ou pour ceux qui cherchent a complètement éviter une zone de contamination.

Importance: Récemment, le ministère de la défense du Canada ainsi que les ministères de plusieurs autres pays de l'OTAN ont examiné l'enquête aérienne de rayonnement comme solution à certains des problèmes entourant les maneuvres dans les zone contaminée. Ce travail démontre clairement le potentiel ainsi que les limites de cette méthode en ce qui engendre les opérations militaires. Ce travail représente également une méthode avec laquelle des données d'un tel capteur aérien pourraient être analysées afin de produire un produit militaire indispensable.

Haslip D. S., Cousins T., Jones T. A., Bouteilloux Ph., Dhermain J., Clifford E. T. H. 2000. Cartographie des champs de rayonnement gamma de terre-niveau avec le système CRDO de spectrométrie aérienne. DREO TM 2000-121 Centre de recherce pour la défense Ottawa.

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1. Introduction

1.1 The need for airborne gamma-ray spectroscopy

Armed forces today can be exposed to a wide variety of potential hazards, including ionising radiation. Radiation exposure can arise from a number of scenarios including radiological dispersal weapons and sabotaged or damaged nuclear reactors. In many of the scenarios, and all of the ones mentioned above, radioactive contamination can be deposited on the ground over a wide area. This can present a significant problem to the military commander.

One of the commander's main objectives in such a radiation incident may be to determine the extent and severity of the hazard. In order to make such a determination with ground-based radiation survey instrumentation, the commander must send personnel and equipment into the contaminated zone. This exposes the survey personnel to higher radiation doses than they would otherwise receive, and results in contamination of the personnel and equipment. Both consequences can be important and cause a significant disruption in the operation.

Clearly, a much more desirable solution would be to make measurements from an airborne platform above the contaminated field. In this case, contamination of all equipment (including the aircraft) can be minimised by a judicious choice of flight altitude. In addition, by flying above the contaminated field, the radiation dose to which personnel are exposed is also significantly reduced. The much greater speed with which such an aerial survey can be accomplished (versus a ground survey) also results in a smaller stay time, and thus a lower radiation dose to personnel. These considerations make airborne survey an attractive option for the military.

Another key to effective operations in a radioactive environment is the use of spectroscopy. While Geiger tubes or ionisation chambers can provide reasonable measurements of the magnitude of a radiation field, only a spectroscopic measurement can provide unambiguous identification of the radionuclide. Such identification is essential to quantifying the hazard, especially that from internal exposure.

In response to such requirements, DREO has developed the Airborne Gamma-Ray Spectrometer [1]. This device integrates an uncollimated 3"x2" NaI(Tl) detector with GPS input to create a dose-rate map of the radiation field as a function of position. The system can be man-carried, or installed in either a ground or air platform.

1.2 The challenge of airborne radiation measurement

Of course, it is not sufficient for an airborne radiation measurement system to simply measure the radiation field at some altitude. In order for the system to be truly useful to the military, it must be capable of divining radiation dose rates at ground level from those measured at altitude. This is relatively simple when the radiation derives from a

point source of radiation on the ground. In that case, the dose rate at ground level is related very simply to the dose rate at the flight altitude by the inverse square law for radiation. Thus, one can use the inverse square law to calculate a so-called "altitude correction factor" to convert the airborne measurements into ground-level dose rates. However, the same procedure is not valid when the radiation source is distributed over a wide area. The challenge in this case is significant, and an approach to its solution is presented herein.

2. Experiment

DREO's Airborne Gamma-ray Spectrometer was field tested in September 1999 at the Division Décontamination et Études de Protection (DEP) [2] at the Établissement Technique de Bourges (ETBS). This French military facility near the city of Bourges is permitted to spread radioactive ^{140}La (at most 10 Ci) over an 80 m by 80 m field at various contamination levels and in any number of patterns.

For this experiment, the ^{140}La was spread in two diagonally opposite quadrants of the field, and not in the others. The contamination levels measured by the DEP personnel following the spreading are shown in Figure 1. The contamination is assessed through the use of "witness plates". These square metallic plates are placed at many locations throughout the field just prior to the contamination of the field and are removed immediately after. The contamination level (activity per unit area) on a given plate is thus the same as that of the field in the same area. The plates are then placed in a fixed-geometry, calibrated device that determines the activity per unit area on each plate (and, by inference, on the field). In addition, following contamination, dose rate measurements at the NATO standard height of 1 m were made in the field with a Microspec NaI(Tl) spectroscopy system [3]. The contour plot of the dose rates is shown in Figure 2. In general, the dose-rate contours follow the contamination contours. The dose rates vary by well over an order of magnitude, from around 1 μSv/h to 60 μSv/h.

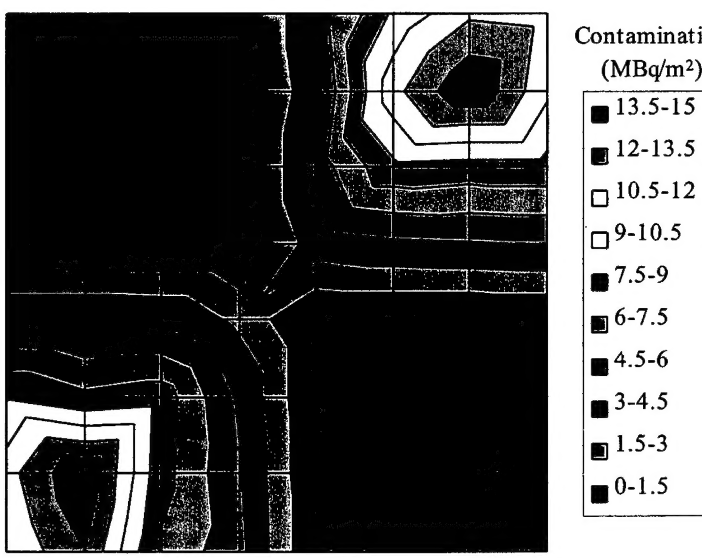

Figure 1. *Measured contamination levels in the Bourges field. Each square is 10 m by 10 m.*

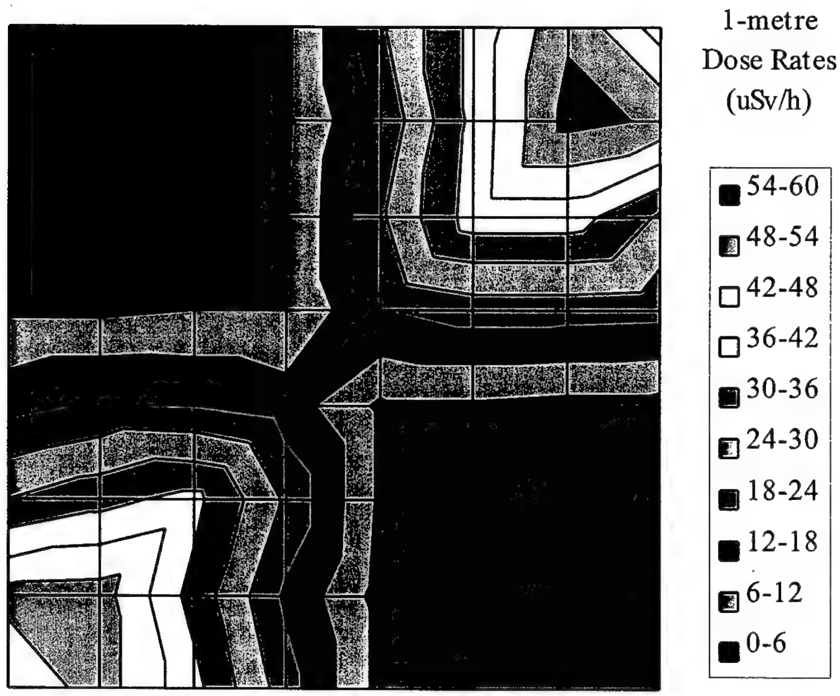

Figure 2. *Measured dose rates at 1 m above the contaminated field.*

The French military also provided a helicopter for these trials. It made a series of three flights over the contaminated field. Each flight consisted of a series of approximately ten straight-line passes over the field, so that the radiation field was measured in a raster-like fashion. The three flights were at altitudes near 20 m, 50 m, and 100 m.

The Airborne Spectrometer normally uses Differential GPS input (DGPS) to achieve 5-10 m accuracy in position. In Bourges, however, there is no available DGPS beacon. To remedy this situation, a second fixed GPS receiver ran during the trials, logging the signals from the satellites in the GPS constellation above Bourges. This fixed system was thus able to correct for the dither and other inaccuracies in the signals from the GPS satellites and correct the data measured in the helicopter after the flight. This permitted position measurements to within 1 m.

3. Airborne measurements

The dose rates measured by the Airborne Spectrometer at 20 m, 50 m, and 100 m are shown in Figure 3; the 1-m measurements from Figure 2 are also shown for reference purposes. Three trends are instantly clear:

1. Maximum dose rate falls off significantly with altitude.

2. The shapes of the dose rate contours at a height of 1 m are not the same as at higher altitudes, and the discrepancy increases with altitude. At 50 m, it is no longer clear that there are two patches of contamination on the ground.

3. The uniformity of the dose rates increases with altitude. At 100 m the ratio of the highest dose rate to the lowest dose rate over the field is approximately 1.5, while at 20 m this ratio is approximately 10, and at 1 m, the ratio is approximately 60.

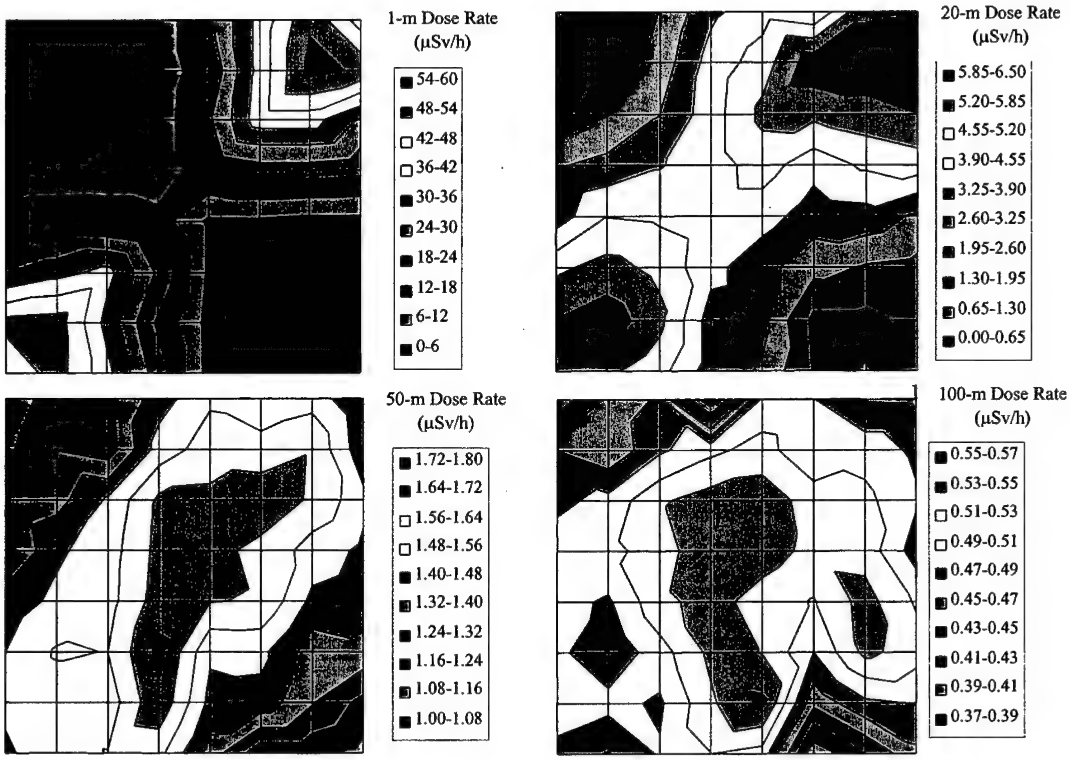

Figure 3. *Dose rates measured at 1 m, 20 m, 50 m, and 100 m above the contaminated field. The 1-m measurements were made with a hand-held gamma-ray spectrometer; the latter three sets of measurements were made with the DREO Airborne Spectrometer.*

The first trend is a result of the inverse-square law for radiation, and was previously identified as a justification for airborne measurements. The latter two effects have a related origin, namely that, as the altitude increases, the distance from a given point on the ground to any point above the field is increasingly insensitive to the horizontal range. Thus, since dose rate depends on the distance between the source and the measurement point, a contaminated spot on the ground produces an increasingly uniform dose-rate distribution as a function of horizontal range as the altitude increases. This can also cause changes in the shape of the dose rate contours as a function of altitude, if the radiation distribution on the ground is non-circular. Atmospheric scattering of the gamma rays will also tend to contribute to the distorting of the dose-rate contours and the increased uniformity of the dose rates at higher altitudes. Qualitatively, therefore, these data patterns are as expected.

It is worth noting that, since the shapes of the contours change with altitude, it is clearly impossible to derive ground-level (1-m) dose rates by dividing airborne measurements by a constant altitude correction factor. Determining 1-m dose rates clearly requires a more sophisticated approach, and this issue is addressed in the next section. Of course, altitude correction factors can be a useful first approximation, and the data from these trials could be used to derive such quantities.

4. Calculating dose rates above contaminated fields

4.1 Microshield calculations

In order to determine whether it is possible to determine contamination levels from airborne measurements, one must first ask whether the inverse procedure is possible. That is, can one reconstruct dose rates at various altitudes given the contamination levels on the ground? This subsection addresses that question.

A number of computer codes are currently available that can predict radiation dose rates at various distances from radioactive sources of specified geometry. Several of these were tested against dosimetry measurements at DEP. One of these is Microshield [4], a commercial code developed by Grove Engineering. This program was used to develop the preliminary calculations that are described in this section.

The radioactive source for these calculations consists of a circular patch of "wet sand", with an area of 100 m^2, uniformly contaminated with ^{140}La to a depth of 2 cm. The "wet sand" is a user-customised material consisting of silicon dioxide (75% by weight) and water (25% by weight) with a density of 1.11 g/cm^3. The source dimensions are a compromise between reality and what Microshield can model. The planned contamination pattern was based on 10 m by 10 m squares of uniform contamination. Thus, the ideal calculation would use that as a source term. However, Microshield cannot calculate rates at arbitrary positions around a square source. Thus, a circular source of the same area was taken instead. The contamination level was 1 MBq/m^2, although this is simply a calculational convenience and the result is scaled later in the calculation.

The 2 cm depth of the source is an empirical parameter that is sometimes called the "effective depth" or the "ground roughness"[5]. It is a reflection of two facts:

1. The source is not an infinitely thin flat plane, but is dispersed throughout the top centimetre of soil [6].

2. Even if the radioactive agent is right at the surface, irregularities in this surface will result in suppression of the dose rate near the ground, as if the agent were distributed through the top few centimetres [7].

Calculations for a 5 cm depth were also performed and will be discussed below.

Dose rates were calculated at heights of 1 m, 20 m, 50 m, and 100 m above this source, at selected horizontal distances ranging from 0 m to 226 m from the centre of the source. The horizontal distances were chosen to lie at the lattice points of a square grid of side length 10 m, once again recognising the scale of the contamination pattern. Some of the results of these calculations are shown in Figure 4. This graph shows quantitatively the main point addressed in the previous section; that is, that the dose

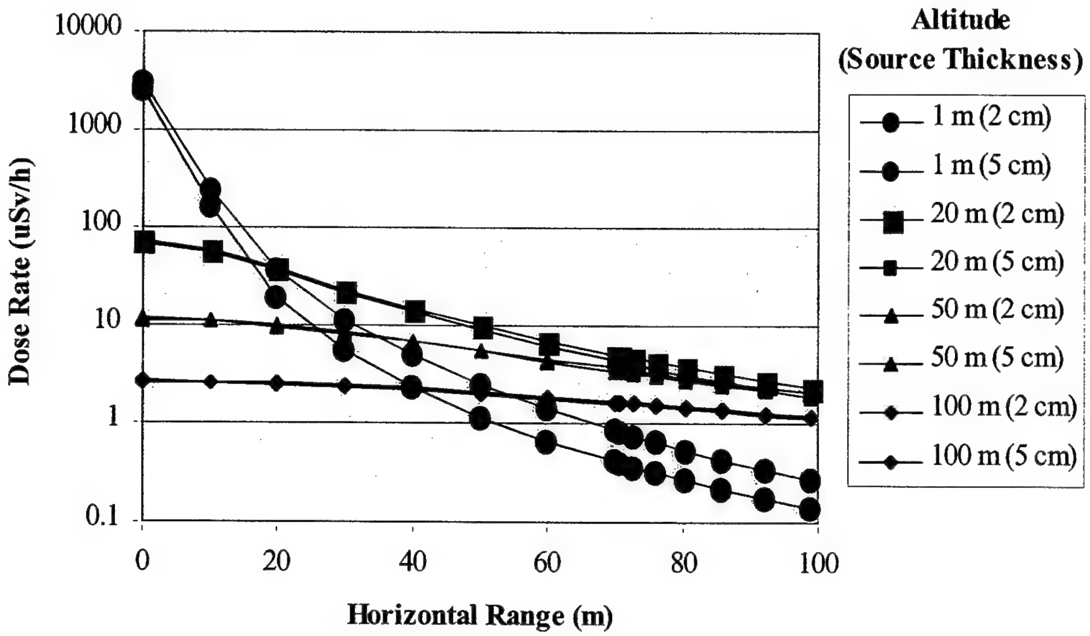

Figure 4. *Dose rate as a function of horizontal range, for several altitudes above the source and two source thicknesses (the contamination level was 1 MBq/m²). Note that only the values at 1 m depend sensitively on the source thickness.*

rate is less sensitive to horizontal range as the altitude increases. It also shows the effect of changing the depth of the source, minor except at ground level.

The implication of this is important operationally. For operations in a contaminated field, one of the most important quantities is the contamination per unit area, since the internalised dose can be calculated from this quantity [8]. Since the dose rates at flight altitudes are only marginally impacted by ground roughness, calculation of ground contamination from airborne measurements (and thus internalised dose) should be relatively independent of one's model of surface roughness. However, unless the surface roughness assumptions are correct, it will not be possible to derive ground-level dose rates from airborne measurements.

4.2 Calculation of airborne dose rates

Based on the results of the previous section, it is a relatively simple exercise to calculate the dose rate above the contaminated field at DEP. For each of the sixty-four 10 m by 10 m segments of the field, the measured contamination level is used to determine the dose rate at a given altitude on the same 10 m grid. The results are then added together to give the total expected dose rate at that altitude. A constant

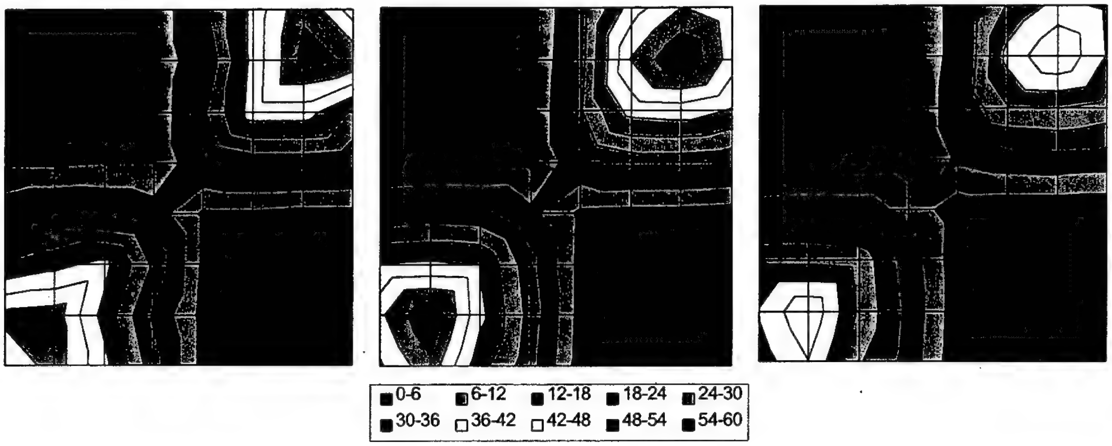

Figure 5. Dose rates (in μSv/h) at a height of 1 m above the contaminated field. From left to right, the plots show (left) measured rates, (centre) calculated rates for 2 cm effective depth, and (right) calculated rates for 5 cm effective depth.

background dose rate of 0.05 μSv/h is also added on to these data. This was determined from airborne spectrometer data taken as the helicopter took off in a completely uncontaminated area.

Figure 5 shows the measured dose rates at 1 m above the field, along with calculations of this dose rate for effective depths of 2 cm and 5 cm. Although neither calculation perfectly replicates the measured dose rates, the calculation for 2 cm effective depth comes very close to reproducing the measured data and is clearly much better than the 5 cm calculation. Thus, for the remainder of this paper, the 2 cm calculations will be used. One notable difference between the measured and calculated distributions is that the measured contours are more irregular than the calculated ones. This is an inevitable consequence of (a) differences between the actual distribution of contamination in the field and the idealised distribution that has been assumed for these calculations, and (b) statistical fluctuations and experimental uncertainties inherent to the dose rate measurement.

Figure 6, Figure 7, and Figure 8 show the measured and calculated dose rates for altitudes of 20 m, 50 m, and 100 m, respectively. The percent discrepancies between the measured and calculated rates are also shown. Once again, the measured contours are considerably more irregular than the calculated ones, as a result of irregularities in the contaminated field and statistical fluctuations or experimental uncertainties in the measurement. This latter effect is more important at higher altitudes where the dose rates are lower. The calculated values also consistently over-estimate the dose rates; this is probably due to the shielding of the helicopter within which the sensor was placed. The over-estimation is not large, amounting to only about 20%. Overall, however, the agreement between the measurements and the models is good, especially at the lowest altitude.

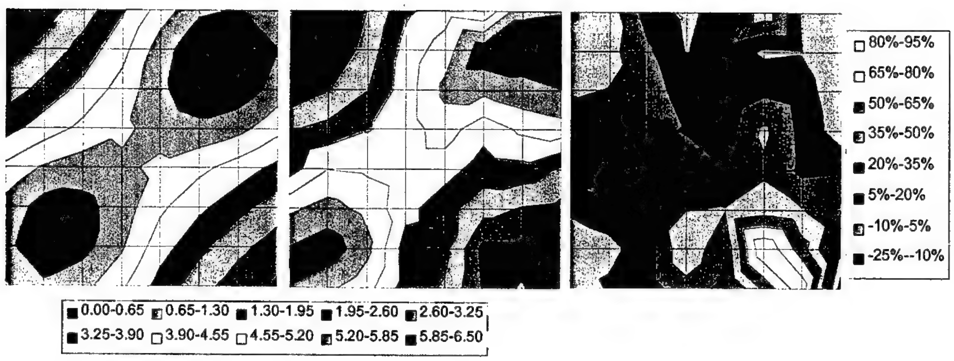

Figure 6. *Calculated (left) and Measured (centre) airborne dose rates (in μSv/h) for an altitude of 20 m. The agreement is generally good, except that the calculated distribution is much smoother. The percentage deviations between the two (right) are mostly less than 30%.*

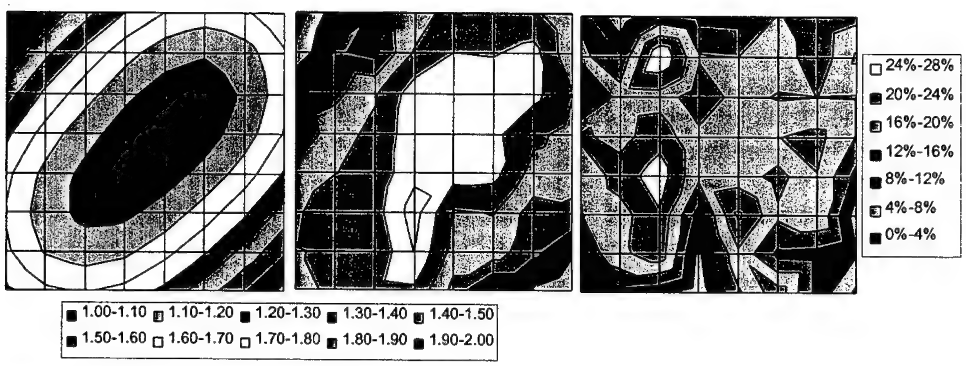

Figure 7. *As above, but for an altitude of 50 m. Note the suppressed zero in the scale of the left and centre plots (ie: the legend only extends down to 1 μSv/h), which accentuates differences between the two distributions. The percent discrepancy is mostly constant, at about 20%.*

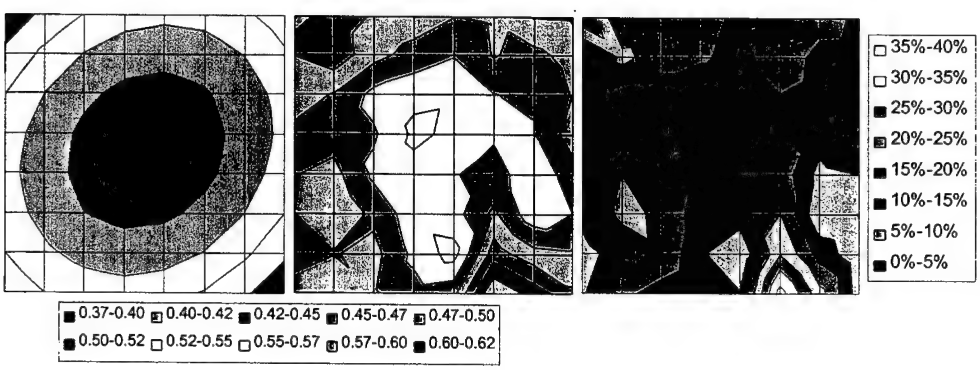

Figure 8. *As above, but for an altitude of 100 m. Again, note the suppressed zero in the scale, and the constancy of the percent discrepancy at 15%.*

5. Calculating ground-level dose rates from airborne measurements

5.1 Method

Developing a method of determining ground-level contamination or dose rates from airborne measurements is essentially a question of reversing the procedure from the last section. In this case, given a contamination pattern on the ground, one can calculate the dose rates at a given altitude. So, a straight-forward approach would be to perform the following steps:

1. Assume a contamination pattern on the field. For simplicity, also assume that this can be specified as 64 independent parameters $(c_1, c_2, ..., c_{64})$, the contamination of each of the 10 m by 10 m squares of land that make up the contaminated field. Initially, it is assumed that there is no contamination on the field $(c_i = 0, i = 1..64)$, but the result is not sensitive to the original assumption.

2. Calculate the expected dose-rates at the flight altitude (including the 0.05 μSv/h background) above the centre of each of the 64 squares of land. These dose rates $(d_1, d_2, ..., d_{64})$ are each a function of all 64 contamination parameters. That is, $d_1 = d_1(C_1, C_2, ..., C_{64})$.

3. Calculate a χ^2 figure of merit for this distribution, given by the sum of the squared deviations between the measured D_i and calculated d_i dose rates, as illustrated in the equation below (the measured rate is an average of dose rates measured over that region of the field):

$$\chi^2 = \sum_{i=1}^{64} (d_i(c_1, c_2, ..., c_{64}) - D_i)^2$$

4. Iteratively, adjust the contamination pattern until χ^2 is minimised.

Thus, the problem is reduced to minimising a function of 64 parameters. This was accomplished with a C program implementing the Powell's Direction Set Method [9] of function minimisation. Run times for this program were generally under two minutes when run on an IBM PC with a 500 MHz Pentium-3 processor. The results of this approach are discussed in the following subsection.

5.2 Results

Figure 9 shows the measured contamination levels and those determined from analysis of the airborne data taken at 20 m. The differences are substantial; the computations

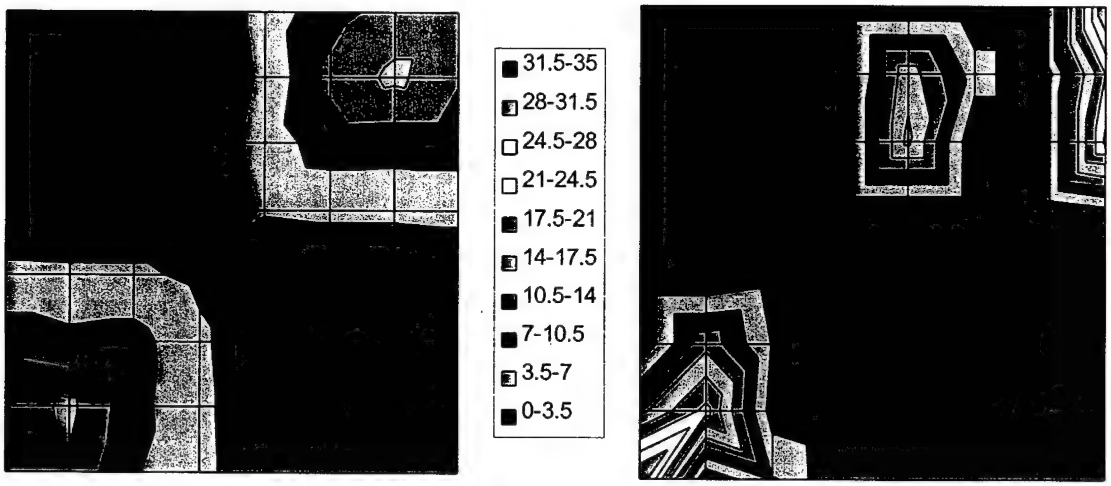

Figure 9. *Left panel – measured contamination of the DEP field. Right panel – contamination levels inferred from 20 m airborne data. Contamination is given in MBq/m^2.*

predict smaller regions of much higher contamination than what was actually present. Nevertheless, it is important that the program correctly identified both the most highly contaminated areas and those without contamination. Such information would be invaluable, for instance, in planning a route through a non-uniformly contaminated region.

While the "fundamental" quantity for comparison is the contamination level, perhaps a more important quantity is the dose rate at one metre. It is the dose rate that determines to what extent a soldier traversing the area will be exposed; although the contamination level is vitally important to evaluating inhalation or ingestion, it is unlikely that any armed force would undertake a planned traversal of such a region without respiratory protection. The measured and calculated one-metre dose rates are compared in Figure 10. The discrepancies between the two plots are similar to those observed in Figure 9, as expected, but they are generally not as significant. Since contamination at one point results in dose rates at all surrounding locations, the "affected" areas are larger for the calculations in this case. Once again, the computations correctly identify the most and least contaminated zones.

Given the significant differences between the calculated and measured contamination levels and one-metre dose rates, it is instructive to consider the calculated and measured dose rates at the flight altitude. This is done in Figure 11. Here, the agreement between measurement and computation is excellent. Indeed, it is a better rendering of the experimental data than what is expected given the measured contamination pattern (see Figure 6). Thus, it is clear that the function minimisation algorithm is working well, and that the inadequacies of the computation in terms of contamination levels or ground-level dose rates is not a problem with the algorithm. Rather, it derives from one or more of the following causes:

1. An inadequate model for how to convert contamination levels into dose rates – this seems unlikely, given the success of this approach for 1 m dose rates (Figure 5).

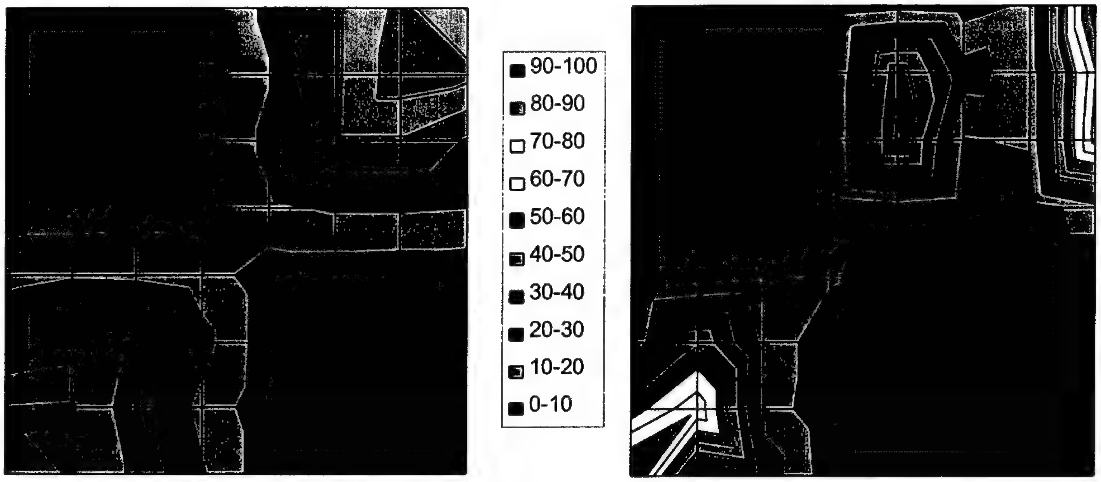

***Figure 10.** Left panel – measured dose rates (in μSv/h) at 1 m above the contaminated field. Right panel - Inferred 1-m dose rates, based on the contamination levels in Figure 9.*

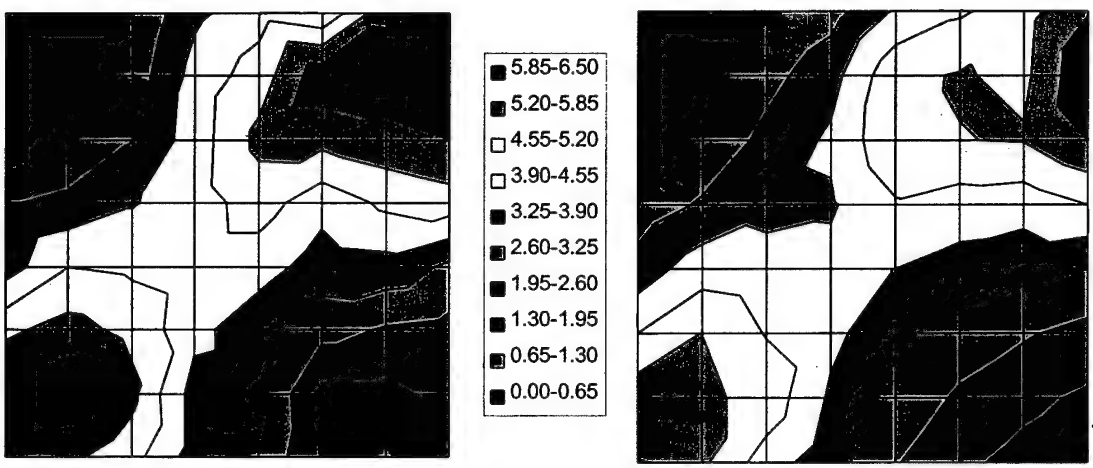

***Figure 11.** Left panel – measured dose rates (in μSv/h) at an altitude of 20 m. Right panel – dose rates at 20 m corresponding to the inferred contamination levels from Figure 9.*

2. The presence of contamination outside of the two specified quadrants, and particularly outside of the 80 m by 80 m field – some amount of such contamination is possible, but this is likely to be small.

3. The problem itself is underdetermined – that is, there are many possible contamination patterns that produce similar dose rate distributions at 20 m. Thus, a measurement at 20 m is insufficient to uniquely define the ground contamination.

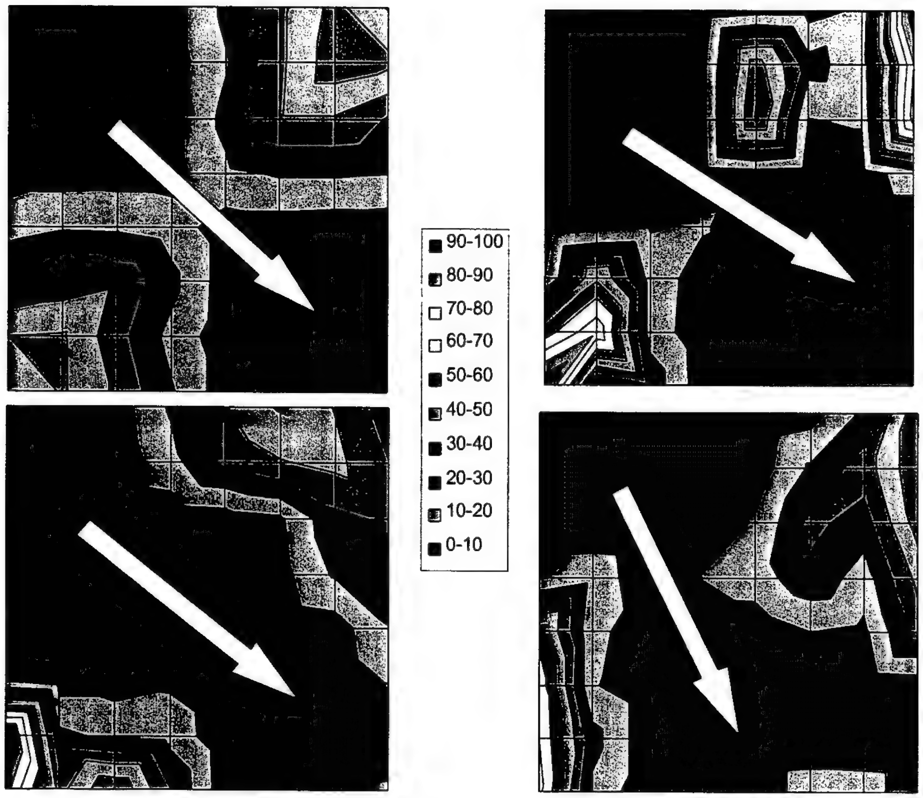

***Figure 12.** Upper left panel – Measured one-meter dose rates (in μSv/h). Other panels – inferred one-meter dose rates, based on airborne data at 20 m (upper right), 50 m (lower left) and 100 m (lower right). The yellow arrows show the path a military commander might choose through the contaminated region to minimise exposure to personnel.*

This last possibility seems the most likely explanation, and is a limitation that must be acknowledged. This can only be truly verified by a more thorough examination of the χ^2 surface, which has not yet been undertaken.

Figure 12 compares the measured 1-m dose rates to the calculation for 20 m, 50 m, and 100 m. All three calculations give more or less the same result. In none of the cases is the dose rate distribution well reproduced. As described above there is a tendency for the algorithm to converge on a solution in which the contaminated region is physically too small, but to compensate for this with contamination levels that are too high. Nevertheless, the calculations never fail to identify two quadrants of contamination and two quadrants of little to no contamination. Once again, this allows a military commander to choose a path through the contaminated field that minimises the exposure to personnel. The arrows in Figure 12 show such paths, and it is clear that the path chosen based on each calculation is quite close to that chosen based on the ground-level measurements.

Thus, the program is a generally successful, but it is demonstrated that airborne measurement is inherently limited in the answers it can provide on ground-level contamination. It is also worth noting that the quality of the result is not sensitive to the altitude at which the measurements are taken. This is important since the flight altitude will often depend on other factors.

It should be noted that two modifications to this algorithm were tested in an effort to improve the accuracy of the result. First, the airborne data from outside the 80 m by 80 m area was used, while still restricting the contamination to the original field. It was felt that the presence of more dose rates (and lower dose rates) outside the field would tend to drive the algorithm towards solutions in which the contamination was not placed so closely to the edge of the field. However, this did not lead to any noticeable improvement.

The second attempt at improving the results of these calculations was based on the assumption that combining the data into 10 m by 10 m bins was the cause of the inaccuracies observed. Thus, instead of binning the data this way, for each iteration, a dose rate was calculated for each individual airborne datum (one is collected every second). Then, the χ^2 statistic used in the fit was the sum (over all data points) of the squared deviations of each datum from the dose rate calculated for that point, not just a sum of squared deviations over the 64 bins. It was thought that this approach might provide the algorithm with enough extra information to properly constrain the fit. However, once again, this did not lead to any noticeable improvement. More importantly, since this approach involves so many more dose rate calculations, and since the calculations themselves are individually more complex, this algorithm took more than an order of magnitude longer to execute, making it infeasible for a field application.

6. Conclusions

DREO's Airborne Gamma-Ray Spectrometer performed extremely well in its latest trials over the contaminated field in Bourges, France. These trials continue to demonstrate the usefulness of this kind of system for making accurate measurements over a wide area while minimising exposure to personnel.

This report has presented a method for extracting surface contamination levels or waist-level dose rates from measurements made from an airborne platform. It has been shown that this method can be effective in making semi-quantitative assessments of the surface contamination from altitudes up to 100 m. Here, "semi-quantitative" refers to the fact that contaminated and uncontaminated areas are correctly identified, and that the calculated levels themselves are within a factor of 3 of the actual values. This permits a similar, and in fact slightly better, assessment of the 1 m dose rates. This approach could easily be generalised to extract ground-level information from data over an arbitrary reconnaissance region.

While the results for the ground-level values are far from perfect, this work has also shown that the calculated contamination levels reproduce the higher-altitude measurements very well. This implies either an insufficient calculation of the dose rate above the field from contamination on the field, or that the problem itself is inherently underdetermined. It is felt that this latter explanation is the correct one. However, it should be noted that this "loss of information" does not appear to be a strong function of altitude above 20 m. This is supported by the similarity in results from calculations employing data from 20 m, 50 m, and 100 m.

Previous work has shown that ground roughness is an important factor in understanding readings from electronic dosimetry worn at ground level. This work demonstrated that extracting surface contamination is not sensitive to ground roughness. However, converting surface contamination into ground-level dose rates is subject to the same uncertainties as interpreting dosimeter readings, as one would expect. Nevertheless, airborne measurement remains an excellent approach to obtaining ground-level information without contaminating equipment or unduly exposing personnel.

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An algorithm is developed and tested that infers a ground contamination pattern from the dose rate patterns measured by DREO's Airborne Gamma-ray Spectrometer. This algorithm is based on a least-squares minimisation, and uses Microshield calculations of dose rates as a function of altitude over a patch of contaminated ground. The algorithm is successful in that it correctly identifies regions of high and low contamination, which would permit a commander to identify areas to avoid, or paths to follow through a non-uniformly contaminated region. However, the contamination pattern predicted by this algorithm is not a high-fidelity facsimile of the actual distribution. The reason for this deficiency is likely that the problem of calculating ground-level contamination patterns from airborne measurements is inherently underdetermined, and evidence is presented to this effect. These results demonstrate clearly the utility of airborne survey for military purposes, and a method of analysing the data from such a platform.

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